

Analysis of High Resolution Upper Ocean Dye Release Experiments Using Airborne LIDAR

James R. Ledwell, MS#12

Eugene A. Terray, MS#11

Department of Applied Ocean Physics and Engineering

Woods Hole Oceanographic Institution

Woods Hole, MA 02543

phone: (508) 289-3305 fax: (508) 457-2194 email: jledwell@whoi.edu

phone: (508) 289-2438 fax: (508) 457-2194 email: eterray@whoi.edu

Miles A. Sundermeyer

School for Marine Science and Technology

University of Massachusetts Dartmouth

706 South Rodney French Blvd.

New Bedford, MA 02744-1221

phone: (508) 999-8892 fax: (508) 999-8197 email: msundermeyer@umassd.edu

<http://www.smast.umassd.edu/~msundermeyer>

Award Number: N00014-08-1-0545

LONG-TERM GOALS

Our long-term goal is to better understand lateral mixing processes on scales of 0.1-10 km in the ocean. This includes the underlying mechanisms and forcing, as well as the temporal, spatial, and scale variability of such mixing. The particular goal of the present work is to directly observe the processes governing lateral stirring at these scales via high resolution dye release experiments using airborne LIDAR. The broad impacts of this research range from a better understanding of ocean ecosystems and ocean health, to improved parameterizations in numerical models, to a variety of other practical purposes.

OBJECTIVES

This one-year study is in preparation for, and in support of, the “Scalable Lateral Mixing and Coherent Turbulence” Department Research Initiative (DRI). Four specific tasks are being undertaken: (1) participate in DRI pre-planning; (2) specify the required LIDAR system characteristics, and identify possible collaborators; (3) improve our LIDAR inversion to obtain dye concentration; and (4) complete the analysis of data from a pilot experiment we previously carried out on the Florida Atlantic Shelf.

APPROACH

Relative to the first objective above, we have participated in planning meetings and significantly contributed to white papers submitted to ONR for the purposes of planning the Lateral Mixing DRI. Relative to the second, we are working with the NAVAIR LIDAR group, led by Drs. Jennifer Prentice and Brian Concannon to identify system parameters for their new LIDAR system that optimally enable them to detect and map fluorescent dye patches. Relative to the third objective, we have been

Report Documentation Page			Form Approved OMB No. 0704-0188		
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE 30 SEP 2008		2. REPORT TYPE Annual		3. DATES COVERED 00-00-2008 to 00-00-2008	
4. TITLE AND SUBTITLE Analysis Of High Resolution Upper Ocean Dye Release Experiments Using Airborne LIDAR				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Woods Hole Oceanographic Institution, Department of Applied Ocean Physics and Engineering, Woods Hole, MA, 02543				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES code 1 only					
14. ABSTRACT Our long-term goal is to better understand lateral mixing processes on scales of 0.1-10 km in the ocean. This includes the underlying mechanisms and forcing, as well as the temporal, spatial, and scale variability of such mixing. The particular goal of the present work is to directly observe the processes governing lateral stirring at these scales via high resolution dye release experiments using airborne LIDAR. The broad impacts of this research range from a better understanding of ocean ecosystems and ocean health, to improved parameterizations in numerical models, to a variety of other practical purposes.					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 6	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

exploring and developing improved methods for inverting LIDAR waveforms to obtain absolute dye concentrations. This includes consideration of LIDAR system characteristics as well as ocean optical properties. Relative to the fourth, we are continuing our analysis of a previous data set collected off the Florida shelf [Sundermeyer et al., 2007; Terray *et al.*, 2005] as a means of testing new inversion approaches, and in an effort to identify potential problems or concerns with the new LIDAR system.

WORK COMPLETED

Regarding DRI planning, to date we have participated in and helped write the white paper for the DRI planning meeting held May 28-30 at MIT, Cambridge, MA. Related to the DRI, we are also coordinating the present research efforts and our upcoming DRI-funded work with a major grant from the National Science Foundation to the PIs (Ledwell, Sundermeyer, Terray).

Regarding LIDAR system characteristics, discussions with our collaborators at NAVAIR are ongoing to identify optimal characteristics of their LIDAR system for dye sampling, including optimal wavelengths for both the laser and the dye receive channels and likely s/n for both backscatter and fluorescence channels. We have also done preliminary modeling of anticipated system characteristics and water properties to identify likely dye detection limits and sampling resolution of the LIDAR. Significant effort was also devoted to an engineering field test in Sept. 2008 off North Carolina in which we tested the NAVAIR LIDAR capabilities for mapping a dye patch injected at 30 m depth in the ocean. As part of the field test, concurrent with LIDAR overflights, we conducted *in situ* measurements of inherent optical properties, dye concentration, CTD and ADCP measurements, and Lagrangian drifter studies to better understand both the scientific and technical challenges of the combined airborne and ship-based sampling program.

Regarding LIDAR inversions to obtain dye concentration, we have been reviewing the literature and exploring various possible improvements to the LIDAR inversion procedure developed for our 2004 Florida pilot experiment. One improvement we are investigating is the inclusion of multiple scattering effects using quasi-analytical approximations for beam propagation when multiple near-forward scattering is important [e.g., Malinka and Zege, 2003; Zege *et al.*, 2004]. A second area of improvement we are investigating is how to incorporate statistical information about the horizontal correlation scale of the dye patch into the inversion, rather than inverting each profile independently as we have done in the past.

Regarding analysis of data from our 2004 Florida pilot experiment, we have continued our data analysis both to better understand the physical mechanisms responsible for the horizontal and vertical spreading in that experiment, and to develop better methods for visualizing and quantifying the observed spreading. As part of this, we have been concerned with, for example, improved methods for tracking individual features in the dye distribution, and better establishing the relationship between these features and other measured quantities such as velocity and density structure.

RESULTS

LIDAR Collaboration and Engineering Field Study: Of the work completed in the current reporting year, our most significant results come from our collaborations with the NAVAIR group to better understand their LIDAR system requirements and limitations, and from our engineering tests conducted off the North Carolina coast, the latter being in effect a culmination of the former.

Operations were carried out within a few nautical miles of 33.8 N, 74.5 W, southeast of Cape Hatteras and off shore of the Gulf Stream in oligotrophic waters (Fig. 1).

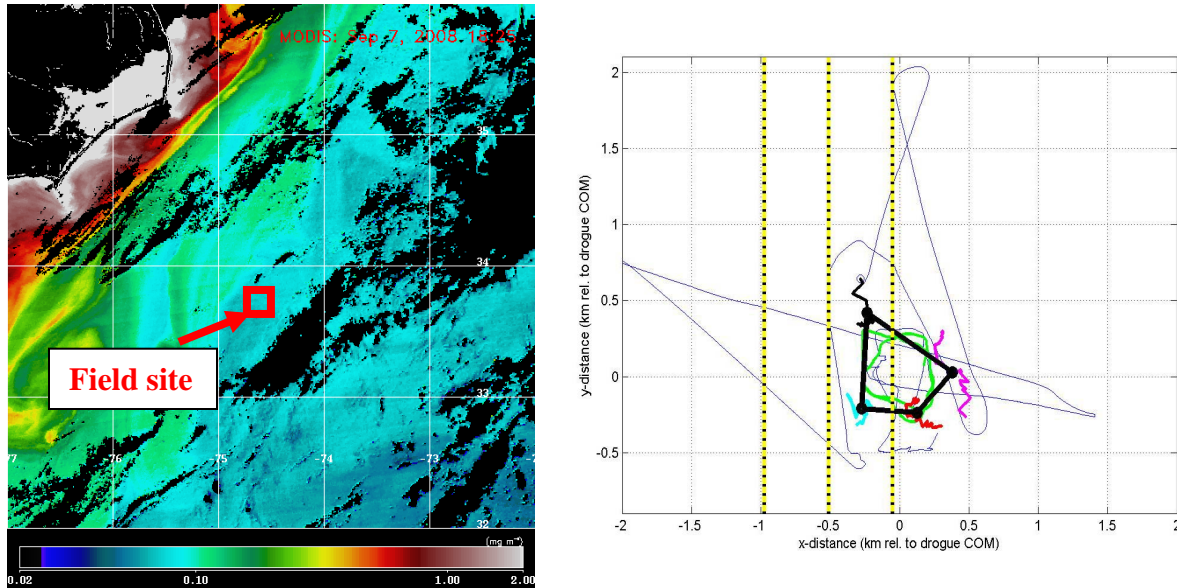


Figure 1: (a) Chlorophyll estimated from the MODIS Satellite on 7 September 2008. Chlorophyll levels near the site at 33.8 N, 74.5 W are approximately 0.08 mg/m³ in this image. Cape Hatteras is visible in the NW corner. (b) Ship track (blue line), drifter tracks (cyan, black, violet, red lines), and aircraft way-lines (yellow/black dashed) relative to the center of mass of the drogues. Dye was injected along the green track. The black polygon indicates the mean position of the drifter box in which dye was injected.

Approximately 7.5 kg of fluorescein dye were injected at a depth of 30 m in a box pattern whose corners were marked by 4 drifters equipped with drogues centered at 30 m. Subsequent to the injection, the dye was surveyed via two tow-yo transects through the patch, after which the vessel stood off while the aircraft conducted its surveys. Following the aircraft overflights, the dye patch was again sampled by the vessel via multiple tow-yo transects. Examples of profiles of dye concentration as a function of depth for the three surveys are shown in Fig. 2.

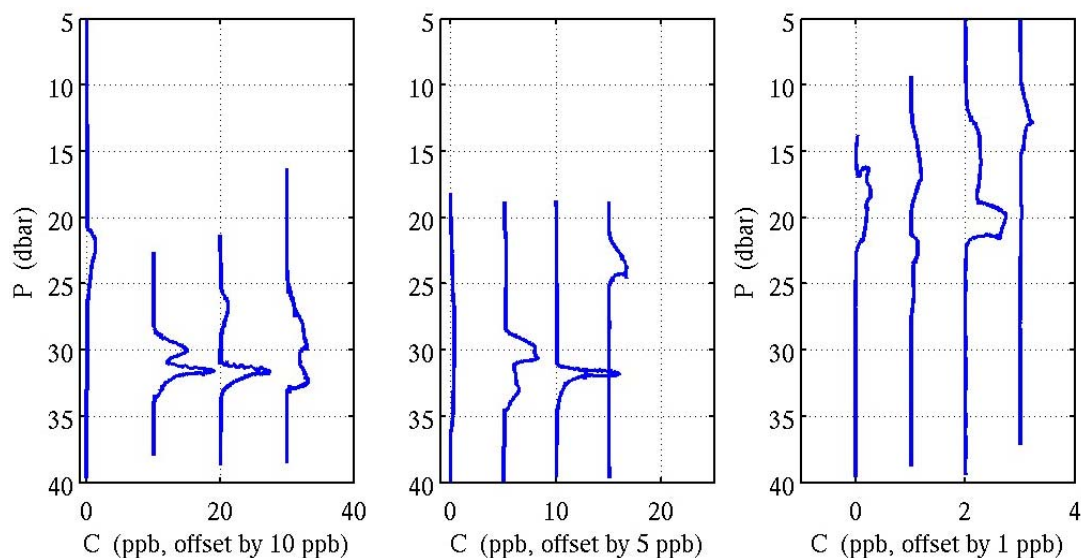


Figure 2: Sample dye concentration profiles as a function of depth taken during the first (left), second (middle), and third (right) surveys of the dye patch showing variability of dye concentration as a function of depth, and decreasing absolute dye concentrations as a function of time.

Absorption and attenuation of the water in the upper 30 meters were measured at nine wavelengths with a WetLABS AC-9. Apparent optical properties of the water were also measured using a Satlantic SPMR Radiation Profiler a few hours preceding the dye injection in order to better understand in situ conditions for the LIDAR, and to use in the inversion of the LIDAR signal for absolute dye concentration. The SPMR measures downwelling irradiance (ED) at 411, 442, 490, 509, 554, 665, and 684 nm, and upwelling radiance (LU) at nominally the same wavelengths. A reference radiometer was mounted on the roof of the winch house on the vessel to read the incident downwelling irradiance at the surface (ES). Figure 3 shows the results from Profile 2, taken on 9/9/09, in semilog coordinates for the three frequencies of most interest. Frequencies 442 nm and 490 nm bracket the LIDAR frequency, which is at 470 nm. 509 nm is near the wavelength of the fluorescein emission of 515 to 520 nm.

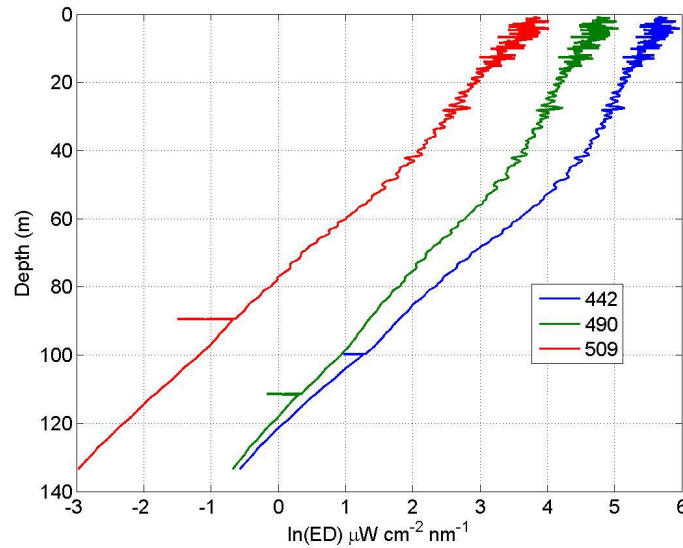


Figure 3: Downwelling radiation profiles from the SPMR, Profile 2, 9/9/08. The 442 nm profile has been offset by 1 unit to the right; the 509 nm profile one unit to the left for clarity. Optical depths for diffuse radiation can be estimated roughly from the depth over which the natural log of the radiation decreases by 1 unit.

A major result from the field test is that the airborne LIDAR was readily able to detect the dye patch in both the backscatter signal at 470 nm and in the fluorescence channel at 515 nm. Figure 4 shows results from the fluorescence channel. Bands on the left are possibly the signature of internal waves. The signal from the patch on the right was so strong as to saturate the detector. A more detailed analysis of both the LIDAR and *in situ* data sets is ongoing.

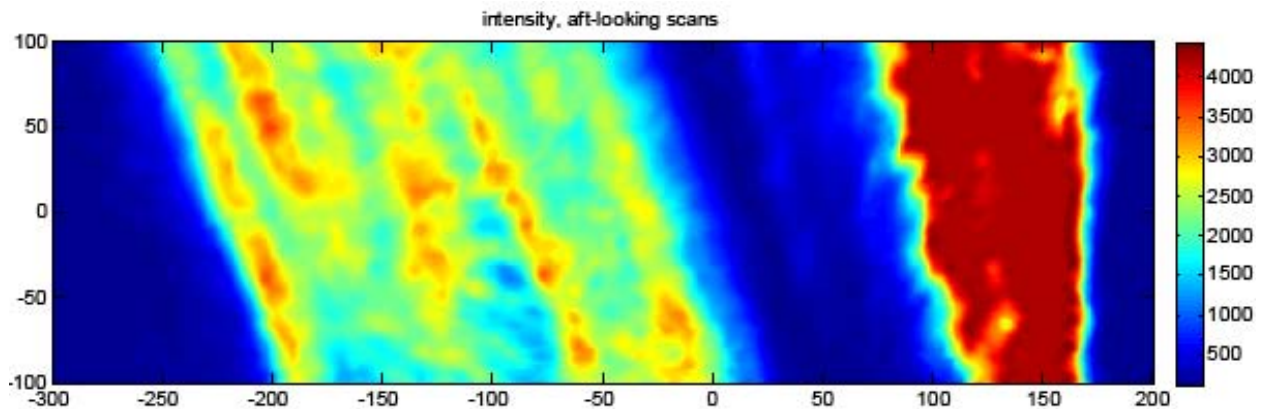


Figure 4. LIDAR signal from an overflight. The flight path was from left to right. Horizontal axis: along track distance, in meters; Vertical axis: cross-track distance, in meters. Color: the maximum signal recorded, regardless of depth, in the green, fluorescence, channel. The deep red at the right of the figure indicates saturated signal, so the peak is off scale. The depth of the stripes on the left was 20 to 25 m; the depth of the red saturated patch on the right was 10 to 20 m. Courtesy of Jeffery Lee (APL/JHU) and Brian Concannon (NAVAIR).

Continued Analysis of 2004 Florida Pilot Study: As part of our continued analysis of our 2004 Florida Pilot Study data, we have identified a likely mechanism for the dispersion observed in our

Florida pilot experiment, namely, roll vortices associated with rotational shear in the upper water column. A conference presentation on these results was given at the 2008 Ocean Sciences meeting in Orlando, FL. In addition, preliminary LES simulations have been conducted in collaboration with Dr. Ramsey Harcourt at APL/UW to better understand the forcing and scales of these roll vortices.

RELATED PROJECTS

The PIs efforts under the current ONR project as well as the upcoming ONR DRI is being performed in coordination with the PIs efforts under a related NSF project entitled “Collaborative Research: LIDAR Studies of Lateral Dispersion in the Seasonal Pycnocline”, NSF Award # OCE-0751734.

REFERENCES

Malinka, Alexey, and Eleonora P. Zege, 2003: Analytical modeling of Raman lidar return, including multiple scattering. *Appl. Opt.* **42**(6), 1075-1081.

Sundermeyer, M.A., E.A. Terray, J.R. Ledwell, A.G. Cunningham, P.E. LaRocque, J. Banic, and W.J. Lillycrop, 2007. Three-Dimensional Mapping of Fluorescent Dye Using a Scanning, Depth-Resolving Airborne Lidar. *J. Atmos. Oceanic Technol.*, **24**, 1050–1065.

Terray, E.A., J.R. Ledwell, M.A. Sundermeyer, T. Donoghue, S. Bohra, A.G. Cunningham, P.E. LaRocque, W.J. Lillycrop, and C.E. Wiggins (2005). Airborne fluorescence imaging of the ocean mixed layer. *Proc. IEEE/OES 8th Working Conf. on Current Meas. Technol.*, 76–82.

Zege, Eleonora, Iosiif Katsev, Alexander Prikhach and Alexey Malinka, 2004. Elastic and Raman lidar sounding of coastal waters. Theory, computer simulation, inversion possibilities. *EARSeL eProceedings* **3**, 2/2004.

PUBLICATIONS

Ledwell, J. R., M. A. Sundermeyer, E. A. Terray, L. Houghton, D. Schwartz. Development Cruise for Dye Experiments with Airborne LIDAR, Cruise Report for R/V F. G. Walton Smith Cruise 0813, 7 - 11 September 2008.